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# Development of underwater acoustics laboratory experiments.

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# DEVELOPMENT OF UNDERWATER ACOUSTICS LABORATORY EXPERIMENTS

by

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GRANTHAM, WILEY GEORGE (M.S., Ocean Engineering)

Development of Underwater Acoustics Laboratory Experiments. (June 1970) Abstract of a Master's Thesis at the University of Miami. Thesis supervised by Associate Professor N. L. Weinberg.

The organization and implementation of an underwater acoustics laboratory for graduate students are described. The reasons for selecting a natural body of water as the experimental medium are discussed. Several experiments designed to be conducted in the laboratory are described. Experiments included are the measurement of the equivalent circuit of a piezoelectric transducer, a relative noise spectrum of the medium, the source level of a sound projector, spreading losses in the medium, the reciprocity calibration of transducers, the effects of filtering, propagation anomalies, the cut-off frequency of a waveguide, and transducer array characteristics. Included also are recommendations for expansion of the laboratory facilities, additional experiments, and suggestions for the use of the facilities in student research in underwater acoustics.

THE UNIVERSITY OF MIAMI

# DEVELOPMENT OF UNDERWATER ACOUSTICS LABORATORY EXPERIMENTS

By

WILEY GEORGE GRANTHAM

A THESIS

Submitted to the Faculty
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the requirements for the degree of
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Subject

Development of Underwater Acoustics
Laboratory Experiments

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# PREFACE

Underwater acoustics experiments for a student laboratory was suggested as a subject for thesis research by Dr. N. L. Weinberg, Associate Professor of Ocean Engineering. My personal interest in applications of underwater acoustics stems from prior experience as an officer of the United States Navy. Previous schooling and actual experience in antisubmarine warfare brought me into close contact with underwater acoustics as related to sonar and other ASW applications. In my future career as a naval officer, it is probable that I will be assigned as an instructor in antisubmarine warfare or perhaps underwater acoustics specifically, at either at the U.S. Naval Academy or one of the Navy's ASW schools. If so, the experience gained at the University of Miami will stand me in good stead. If not, there will be many other opportunities to apply knowledge of underwater acoustics in future assignments.

I am very grateful to Dr. Weinberg, my advisor in this undertaking, for his wise counsel and patient guidance. The students enrolled in the first course in which the experiments included in this paper were used have provided many helpful suggestions. They have also consented to my using their experimental data to illustrate certain concepts. Most of the experiments, however, were performed by the author prior to their use in the course.

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GLOSSARY OF SYMBOLS USED
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| | |
|---|---|
| $k$ | wave number |
| $h$ | depth |
| $f$ | frequency |
| $\omega$ | radian frequency |
| $c$ | propagation velocity |
| $\lambda$ | wavelength |
| $C_0$ | shunt capacitance |
| $R_0$ | leakage resistance |
| $R_R$ | radiation resistance |
| $C_M$ | motional capacitance |
| $L_M$ | motional inductance |
| $R_M$ | motional resistance |
| $\rho$ | density |
| $S$ | surface area |
| $Z_M$ | motional impedance |
| $Z\angle\theta$ | complex impedance |
| $Y\angle\phi$ | complex admittance |
| $G$ | conductance |
| $B$ | susceptance |
| $j$ | $\sqrt{-1}$ |
| $G_M$ | motional conductance |
| $B_M$ | motional susceptance |
| $G_B$ | blocked conductance |

| | |
|---|---|
| $B_B$ | blocked susceptance |
| $\omega_0$ | resonant radian frequency |
| $\omega_1$ | quadrantal radian frequency one |
| $\omega_2$ | quadrantal radian frequency two |
| A | current |
| V | voltage |
| P | power |
| I | intensity |
| r | linear distance |
| p | pressure |
| $L_0$ | inductance to resonate with $C_0$ |
| u | particle velocity |
| $p_A$ | pressure amplitude |
| e | mathematical exponential |
| t | time |
| $S_R$ | receiver sensitivity |
| $V_R$ | receiver voltage |
| $p_R$ | receiver pressure |
| $S_0$ | source level |
| $p_0$ | reference pressure |
| $V_P$ | projector voltage |
| $N_W$ | propagation loss |
| $S_T$ | transmitter sensitivity |
| Q | strength of a sound source |
| $p_P$ | projector pressure |
| $I_P$ | projector current |
| J | reciprocity parameter |

| | |
|---|---|
| $I_1$, $I_2$, $I_3$ | input currents of projectors |
| $V_1$, $V_2$, $V_3$ | output voltages of hydrophones |
| $\theta$ | angle between acoustic ray and horizontal; also defined for an array axis (Figure 8) |
| n | mode number; also number of elements in an array |
| $\varepsilon$ | phase shift angle |
| $p(\theta)$ | pressure at angle $\theta$ |
| $\psi$ | angle used in directivity pattern equations |
| a | distance between array elements |

# I. INTRODUCTION

The University of Miami Department of Ocean Engineering at this time offers two lecture courses in underwater acoustics, both of which stress the theory of propagation of sound in water. During the spring semester of 1969, Dr. N. L. Weinberg of the Ocean Engineering Department proposed that a laboratory course in underwater acoustics be developed. The proposed course was designed to supplement the existing courses with laboratory experience in the equipment and techniques of practical underwater acoustics applications. In January 1970, OEN 634, a graduate level underwater acoustics laboratory course, was incorporated into the ocean engineering curriculum. This paper is the result of the experience the author has gained in assisting in the planning and implementation of the laboratory facilities and in devising the experiments to be conducted in the course. Included also are recommendations for further expansion of the facilities, additional experiments, and suggestions for the use of the facilities in student research in acoustics.

During the initial planning of the course, it was decided that the bulk of the experiments would be conducted in the open water of Bear Cut adjacent to the Institute of Marine and Atmospheric Sciences complex on Virginia Key. The use of the open water medium rather than anechoic tanks presented several problems, some of which have not been completely resolved to date. The advantages of the open water medium, however, were considered to outweigh the disadvantages.

Foremost among the advantages of the open water medium is the experience that will be gained by students in dealing with the problems associated with experiments using actual acoustics components in the natural medium rather than in tanks using frequency scaling. Students will encounter propagation anomalies due to environmental factors of a similar type that may be expected in practical underwater acoustics applications. The ambient noise levels of Bear Cut will closely resemble those encountered in practice, which is not true of a laboratory tank. Frequency scaling is unnecessary in the open water medium, so that both electrical and acoustic equipment can be operated at frequencies comparable to those found in actual applications. The cost of using anechoic tanks is greater than the costs associated with using the open water medium. Finally, Bear Cut, with a pier and an instrument tower already constructed, was readily available to the Ocean Engineering Department for the conduct of student experiments. It should be noted that these facilities available to the University of Miami provide an advantage that few other institutions have for this type of course.

Probably the biggest disadvantage in using a natural body of water as the experimental medium is the lack of control over environmental factors. Temperature, sea state, and salinity of the water all affect sound propagation to some degree. Tidal currents can induce flow noise in hydrophones and displace equipment from selected positions. Bottom bathymetry and composition as well as the physical dimensions of Bear Cut will affect some types of experiments. Another problem in conducting the course will be the transportation of equipment to and from the area where it will be used. A diagram of the IMAS layout and Bear Cut is provided for reference in Figure 1. Many of the experiments call for

either transmitting or receiving equipment to be located at the instrument tower which stands in the Bear Cut channel about 600 feet from the end of the IMAS pier. Boat schedules must therefore be arranged. Some kind of communications link between the tower and the pier is also necessary. Nearly all of the experiments require equipment on the pier. Since there is no suitable permanent housing for equipment on the pier, equipment for the various experiments has to be transported from and to the interior laboratory room and storage area during each session.

The transportation of equipment could be reduced if an appropriate electrical link connected the tower, the pier, and the interior laboratory room. If the electrical cables were properly shielded for the transmission of signals between the three stations, most electrical equipment could be permanently housed in the laboratory room. Only equipment such as transducers and preamplifiers would have to be transported. There is presently a seven-conductor underwater/underground electrical cable installed between the three stations as indicated in Figure 1. The electrical characteristics of the cable are unsatisfactory for the purposes of the laboratory, however. Extensive tests of both one-way and two-way transmission of acoustically-induced electrical signals have indicated that outside interference as well as crosstalk between conductors is so prevalent as to preclude the effective transmission of the necessary signals. The filters available to the laboratory also proved inadequate to overcome the limitations of the installed cable.

There are many pieces of electronic equipment in the IMAS complex and surrounding area, some of which are sources of electrical interference at the frequencies of interest. In addition to the interference

picked up by the cable, electrical interference has been found in the power supply line on the pier and in the laboratory. The strongest interference consists of sporadic bursts of pulses at a repetition rate of about 120 to 160 Hz. The Decca Hi-Fix navigation equipment, another source of interference, is suspected of inducing ground waves as well as radiation interference. Although not yet proven, it is suspected that ground waves are occasionally detected by submerged hydrophones. A wealth of acoustic noise from sources such as boat traffic and pile driving can also be found at various times in the Bear Cut area.

A recent survey of a cross section of Bear Cut between the pier and the tower indicates that the bottom is relatively smooth (1). The depth of water at the end of the pier is 11.2 feet (at mid-tide). The depth at the tower is 14.7 feet. The average depth between the tower and the pier is 13 feet, and the slope of the bottom is less than 1 degree. The bottom composition is sand over limestone. Using Shumway's data (2), the estimated acoustic impedance of the sand layer is about 3400 MKS rayls. These physical limitations of the chosen medium can be compensated for in various types of experiments by varying the operating frequency and the geometry of the experiments.

As an example of changing the experiment parameters to suit the dimensions of the medium, consider the normal mode approach to the theory of underwater sound propagation as opposed to the ray path approach. The former is basically a "shallow water" theory, while the latter is primarily a "deep water" theory. A more rigorous criterion for the use of one as opposed to the other is the ratio of the wave length of the acoustic signal, $\lambda$, to the depth of the water, h, or, as expressed by Tolstoy and Clay, shallow water propagation theory is

in order when (3)

$$kh \leq 10, \tag{1a}$$

where k is the wave number of an acoustic wave. In the case of Bear Cut, h is fixed at approximately 13 feet, so the condition for shallow water propagation is

$$k \leq \frac{10}{13} . \tag{1b}$$

If $\omega/c$ is substituted for k, giving the relation

$$\frac{2\pi f}{c} \leq \frac{10}{13} , \tag{1c}$$

it can be seen that an experiment illustrating normal mode theory as opposed to ray theory would vary the parameter of operating frequency, since c, the propagation velocity in the medium, is fixed.

The following equipment is considered the minimum required for an open water laboratory course in underwater acoustics. (Appendix A lists all equipment presently available to the OEN 634 laboratory.) An adequate supply of rugged, preferably inexpensive sound projectors and hydrophones is essential. Durability and economy are more important for laboratory applications of transducers than sophisticated frequency and directional responses. Because of their durability, efficiency, ease of maintenance, and importance in the field, piezoelectric transducers were chosen as the basic laboratory projectors and hydrophones. The electronic equipment required includes an audio oscillator and an appropriate amplifier for driving the sound projectors, an oscilloscope, amplifier, and filter for processing the hydrophone signals, and auxiliary components such as shielded interconnecting cables, inductors (for resonant operation of sound projectors), impedance matching transformers

(to match amplifier and transducer impedances), and voltmeters. In addition, mechanical devices for conveniently positioning transducers are necessary. (Appendix B contains details of the transducer hanger designed for the course.) The previously mentioned communications system between the tower and the pier is required. An important proposed experiment calls for the measurement of the equivalent circuits of transducers. Some type of complex impedance measuring device is therefore necessary, as is a water container inside the laboratory for transducer immersion.

## II. SUGGESTED EXPERIMENTS

The following experiments are designed primarily to supplement the material presented in the University of Miami's course OEN 535, Introduction to Underwater Acoustics. The experiments follow a logical progression in terms of techniques and principles to be verified. The students first measure the parameters of the transducers which they will be using in later experiments, progress to short-range experiments to acquire familiarization with equipment and techniques, and finally advance to more detailed experiments which illustrate concepts from the lecture courses. Because the students in this laboratory course will not necessarily have an electrical engineering background, and since it is necessary to use electrical equipment in the laboratory, some of the experiments for the course have been designed mainly for equipment familiarization.

The mechanical vibration of a piezoelectric oscillator can be represented by the equivalent electrical circuit which is illustrated in Figure 2. $C_0$ and $R_0$ represent the shunt capacitance and the leakage resistance of the crystal, whereas $R_R$, $C_M$, $L_M$, and $R_M$, the motional parameters, represent the effect of mechanical vibration. $C_0$ is the capacitance that would be measured if the crystal were rigidly clamped so that its dimensions could not change when an electric potential was applied. $R_0$, usually negligibly high, can be measured at very low frequencies when the reactance of $C_0$ is quite high. $R_R$, the radiation resistance, represents the effect of the medium in resisting crystal

vibration. Thus, $R_R$ determines the amount of power transmitted to the medium for a sound projector. $R_R$ represents the value $\rho cS$, where $\rho$ is the density of the medium, c is the speed of sound in the medium, and S is the surface area of the crystal normal to the direction of propagation. $L_M$ and $C_M$ represent the effective mass and the effective stiffness of the crystal, while $R_M$ represents the friction losses. The impedance of the motional branch, $Z_M$, is composed of $R_R$, $R_M$, $L_M$, and $C_M$ in series (4).

The first experiments call for the students to measure the equivalent electrical characteristics of the sound projectors that will be used in later experiments. The concept of the equivalent circuit of a piezoelectric sound projector is illustrated by the measurements made during the experiments. In order to measure a complex impedance such as the impedance of the circuit in Figure 2, it is necessary to employ a bridge which will yield both real and imaginary parts. The instrument used in this laboratory is the Dranetz combined impedance and phase meters, from which the complex impedance, $Z\angle\theta$, can be read. $Z\angle\theta$ is inverted to give the complex admittance, $Y\angle\phi$, from which the conductance, G, and susceptance, B, can be calculated by use of the relation:

$$|Y|\angle\phi = |Y| \cos\phi + j|Y| \sin\phi = G + jB. \tag{2a}$$

The effect of the motional branch of the circuit is negligible at low frequencies, as $C_M << C_0$. Hence, $C_0$ can be measured for most transducers in the neighborhood of 100 Hz. In order to determine $R_0$, the frequency must be lowered to several Hertz. If $R_0$ is not negligible, the complex impedance angle, $\theta$, will depart from 90° at these low frequencies. For most of the piezoelectric transducers encountered, $R_0$ can be neglected. Since the motional parameters have to be found from a plot

of motional conductance, $G_M$, versus motional susceptance, $B_M$, the blocked admittance, $\omega C_0$, must be subtracted from the readings of susceptances obtained. Thus,

$$G_M = G - G_B, \tag{2b}$$

and

$$B_M = B - B_B, \tag{2c}$$

where $B_B$ has the value $\omega C_0$, and $G_B$ has the value $\frac{1}{R_0}$ . $G_B$ is usually negligible compared to $G_M$, as previously stated. Thus, equations (2b) and (2c) become

$$B_M = B - \omega C_0 \tag{2d}$$

$$G_M \simeq G. \tag{2e}$$

B and G, the normally loaded components of admittance in the transducer, are calculated from impedance measurements taken while the transducer (sound projector in this case) is operating in water.* Values of $B_M$ and $G_M$ are obtained for various operating frequencies of the projector, from very low frequencies to frequencies well past the resonant frequency. Most of the readings, however, are taken in the vicinity of resonance of the motional branch.

When values of $B_M$ at frequencies from zero to infinity are plotted against corresponding values of $G_M$, a circle is obtained. An example of this theoretical admittance circle is shown in Figure 3. The equation

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*It has been found in the laboratory that reflections from the water container used for immersion of the sound projector greatly influence the impedance measurements. In the absence of an infinite expanse of water or, more practically, an anechoic tank, excellent results were obtained by loosely wrapping the projector in heavy cloth material. The material effectively shields the projector from reflected pressure waves. Since the wet cloth approximates the acoustic impedance of the water, the impedance measurements remain valid.

of the motional admittance circle may be written in the form (5)

$$[G_M - \frac{1}{2(R_R + R_M)}]^2 + B_M{}^2 = [\frac{1}{2(R_R + R_M)}]^2 . \tag{3}$$

The radius of the circle is $\frac{1}{2(R_R + R_M)}$, and the center is on the $G_M$ axis at $G_M = \frac{1}{2(R_R + R_M)}$. The point where $B_M = 0$ corresponds to the resonant frequency, $\omega_0$, of the motional branch of the transducer. Here, the motional admittance is purely conductive and equals $\frac{1}{R_R + R_M}$. The points where $G_M = \pm B_M$ correspond to the two quadrantal frequencies, $\omega_1$ and $\omega_2$, where the amplitude of the motional branch impedance will be $\sqrt{2}$ times its value at resonance. When $G_M = \pm B_M$, the following relations hold (6):

$$L_M = \frac{R_R + R_M}{\omega_2 - \omega_1} \tag{4a}$$

and

$$C_M = \frac{\omega_2 - \omega_1}{\omega_1 \omega_2 (R_R + R_M)} , \tag{4b}$$

from which two of the equivalent circuit elements can easily be computed.

The value of $R_R + R_M$ is the reciprocal of the circle diameter, but it is necessary now to separate $R_R$, the radiation resistance, from $R_M$, the internal loss term. A sound projector operating in air has almost no effective resistance to the crystal oscillations as compared to the resistance encountered when the projector is operating in water. This is due to the continuity of particle velocity across the face of the transducer and the fact that the acoustic impedance of water is many orders of magnitude greater than that of air. In the case of air as the operating medium, $R_R$ has effectively been removed from the equivalent circuit. The admittance circle that will theoretically be obtained when

the sound projector is operating in air is shown in Figure 3 and may be compared with the circle obtained in water. The diameter of the circle for air will be the reciprocal of $R_M$, just as the diameter of the admittance circle in water was the reciprocal of $R_R + R_M$ (7).

The results obtained by students in measuring the admittance circles of an Edo model 244C piezoelectric sound projector are presented graphically in Figure 4. The following values for the equivalent circuit components were measured or calculated from the admittance circles:

$$C_0 = 24{,}200 \text{ pf}$$

$$R_0 \quad \text{negligibly high}$$

$$L_M = 30.4 \text{ mh}$$

$$C_M = 1940 \text{ pf}$$

$$R_M = 51.6 \text{ ohms}$$

$$R_R = 93 \text{ ohms.}$$

The nominal value of sound pressure transmitted by the model 244C was supplied by the manufacturer. At an operating frequency of 20 KHz, the sound pressure level from the Edo graph was found to be 43.3 decibels per volt reference one microbar at a distance one yard from the projector. The measured value of $R_R$ can be checked with the supplied data by using the following equations:

$$Z_M = (R_R + R_M) + j(\omega L_M - \frac{1}{\omega C_M}), \tag{5a}$$

$$|Z_M| = [(R_R + R_M)^2 + (\omega L_M - \frac{1}{C_M})^2]^{\frac{1}{2}}, \tag{5b}$$

$$A = \frac{V}{|Z_M|}, \tag{5c}$$

where A is the RMS current flowing in the motional branch of the equivalent circuit when an RMS voltage of V is impressed across the projector. Now,

$$P = A^2 R_R, \tag{5d}$$

where P is the acoustic power produced by the projector. The intensity assuming spherical spreading, at a distance r is

$$I = \frac{P}{4\pi r^2}, \tag{5e}$$

where I is average acoustic intensity (8). Using the relation,

$$I = \frac{p^2}{\rho c}, \tag{5f}$$

p, the acoustic RMS pressure (9), can be calculated and converted to db per volt re 1 μb, taking care to use the proper units. The pressure, so obtained by using the measured values in the calculations and appropriate unit conversions, is 129 μb or 42.2 db/volt//μb. This result compares favorably with the nominal data supplied, i.e. 146 μb or 43.3 db/volt//μb. The experimental data differs from the nominal data by 11.6% in terms of acoustic pressure. This difference can be attributed to the errors in phase and amplitude readings and the influence of reflected pressure waves reaching the projector.

As indicated in Figure 2, the power factor of a piezoelectric sound projector can be improved by resonating $C_0$ with an external inductor in parallel. The optimum value of this inductor, $L_0$, can be calculated for the various frequencies at which it is desired to operate the projector by using

$$L_0 = \frac{1}{C_0 \omega_0^2}, \tag{6}$$

where $\omega_0$ is the radian frequency at which $L_0$ will resonate with $C_0$.

The students thus, using the value of $C_0$ which has been measured, can select the inductors desired. Other components of the transmitting circuit are an audio oscillator to provide a sinusoidal signal, a power amplifier to provide the excitation to drive the projector at various frequencies near resonance,* and an impedance-matching transformer to approximately match the output impedance of the amplifier to the impedance of the projector. The transmitting circuit is presented schematically in Figure 5.

The basic components in the acoustic signal receiving circuit are an omnidirectional piezoelectric hydrophone, ** a band-pass filter and amplifier, and detectors such as an oscilloscope and a voltmeter for signal measurement. The basic receiving components are also shown in Figure 5.

In order to familiarize the students with the receiving equipment and with the environment in which they will be conducting experiments, an ambient acoustic noise spectrum of Bear Cut was selected as the next experiment. The experiment calls for the students to employ the hydrophone/filter/voltmeter combination to measure voltages generated by acoustic noise in Bear Cut. The General Radio type 1232-A filter used in the experiment has a fractional bandwidth of about 4%. This means

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*The Edo model 244C transducers available to the laboratory have a relatively high quality factor, making operation at frequencies far from resonance inefficient. This would not necessarily be true for other types of transducers such as electrodynamic, etc.

**Experiments with the Clevite model CH-17 hydrophone have shown that the receiving characteristics are not omnidirectional at frequencies above 10 KHz. Maximum response from the CH-17 is obtained when the circular face of the hydrophone is perpendicular to a line between the hydrophone and the sound source. This characteristic should be taken into account when making measurements by rigidly mounting the hydrophone in the desired orientation to prevent movement of the hydrophone with currents and wave action.

that the bandwidth is 4% of the center frequency of the filter. Since the noise power is expressed on a "per cycle" basis, the bandwidth of the filter at the frequency being measured must be taken into account. If the noise had a flat spectrum over the bandwidth of interest (white noise), an equivalent noise bandwidth could be derived which would be proportional to the bandwidth of the filter. Since the point to be illustrated in this experiment is a relative spectrum rather than absolute values, the bandwidth of the filter is used in calculations rather than applying the correction for the equivalent noise bandwidth. This procedure is also necessitated by the fact that all the students do not necessarily have the required background in random signals and noise to sufficiently comprehend this concept.

In order to measure the noise, a true RMS voltmeter should be employed to determine the noise power at a particular frequency. The relative power in a 1 Hz band obtained in this manner will be proportional to the absolute values of power spectrum levels* achieved through further analysis. Figure 6 shows the spectrum resulting from student measurements in Bear Cut and compares this spectrum with the spectra obtained by Wenz (11). The correspondence between the two spectra is quite good.

After the students are familiar with the transmitting and receiving equipment, they are ready to proceed with the first acoustic measurement employing both systems. The source level of a sound projector is defined as the intensity of radiated sound in decibels relative to the intensity corresponding to an RMS pressure of 1 dyne/cm$^2$ (1 $\mu$b), referred to a

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*Spectrum level refers to the level of a signal contained in a frequency band 1 Hz wide (10).

point 1 yard from the acoustic center of the projector (12). Source levels, thus, are commonly expressed as sound pressure levels, usually in db, referred to a pressure of one microbar.

Source levels are not necessarily measured one yard from the center of the projector. The more common practice is to make sound pressure measurements at a considerable distance from the projector and calculate from the measured quantity the sound pressure level corresponding to the arbitrary one yard reference distance (13). The measurement of sound pressure levels at relatively long distances from the projector insures that the measurements will be made in the far acoustic field. One criterion for determining whether a specific point is in the far or the near field is to examine the equation for particle velocity, u, of a spherical wave:

$$u = \frac{p_A}{\rho c r}\left(1 - \frac{j}{kr}\right)e^{j(\omega t - kr)} , \tag{7a}$$

where $p_A$ is pressure amplitude and other symbols are as previously defined. The term $\left(1 - \frac{j}{kr}\right)$ represents a phase lag between the particle velocity and the acoustic pressure due to the complex acoustic impedance near the transducer. If, however, $\left|\frac{j}{kr}\right| = \frac{1}{kr}$ is much less than 1, the amplitude term approaches 1,

$$\left(1 - \frac{j}{kr}\right) \rightarrow 1 \tag{7b}$$

for

$$\frac{1}{kr} << 1 . \tag{7c}$$

Under these conditions, the phase shift due to the $\frac{1}{kr}$ term may be ignored and acoustic impedance may be considered to be simply $\rho c$.

Recalling that

$$\frac{1}{kr} = \frac{\lambda}{2\pi r} , \tag{7d}$$

it can be seen that the significant factor in determining whether or not a point is in the far field is the ratio of wavelength, $\lambda$, to separation between the projector and hydrophone, r. At a point where separation is greater than a few wavelengths,

$$\frac{\lambda}{2\pi r} << 1, \tag{7e}$$

and the point in question may be considered to be in the far field. A similar analysis for cylindrical waves indicates that the criterion for a point to be in the far field is that

$$(k^2 - \frac{1}{4r^2}) \rightarrow k^2, \tag{8a}$$

which leads to

$$k^2 >> \frac{1}{4r^2} , \tag{8b}$$

or

$$4k^2r^2 >> 1 \qquad (14). \tag{8c}$$

The experiment calls for students to measure modified source levels of the Edo model 244C sound projector at frequencies from about 15 KHz to 20 KHz (near the resonant frequency of the transducer). The wavelength at 15 KHz is 10 cm and at 20 KHz is 7.5 cm, so a separation of 50 cm between the projector and hydrophone will put the hydrophone at least five wavelengths, $5\lambda$, from the projector. In order to simplify unit conversions, the separation for the experiment is maintained at one meter. The standard transmitting and receiving components shown in Figure 5 are used for the experiment. The sensitivity of the hydrophone is assumed to be the nominal value supplied by the manufacturer. By measuring the

voltage output of the hydrophone and the voltage impressed across the transducer, the source level of the transducer can be calculated from the following equations (15):

$$S_R = \frac{V_R}{p_R} , \tag{9a}$$

$$p_R = \frac{V_R}{S_R} , \tag{9b}$$

$$S_0 = \frac{20 \log \frac{p_R}{p_0}}{V_P} \text{ db/volt//}\mu\text{b}. \tag{9c}$$

The symbols in the above equations are defined as follows:

$S_R$ - - receiver sensitivity,

$V_R$ - - RMS voltage out of the hydrophone,

$p_R$ - - RMS pressure into the hydrophone,

$S_0$ - - source level of a sound projector,

$p_0$ - - reference pressure,

$V_P$ - - voltage across the projector.

The data supplied by the manufacturer is presented in db/volt//μb, so the measured levels for each frequency can be compared with the nominal values. The measured source level obtained by students was 34 db/volt//μb at 1 meter at 20 KHz, a result about 9 db lower than the nominal value. The most likely source of error in this measurement is the influence of reflected pressure waves on the hydrophone readings. Ideally, source levels would be measured in a water source large enough to make reflected waves negligible, but in this case, the inevitable reflections from the water surface, the bottom, the pier, and other objects affect the measurements.

Acoustic waves can be propagated in several ways depending on the type of sound source and characteristics of the medium. For instance, an omnidirectional point source in the absence of boundaries will radiate equally in all directions and the radiation pattern will be spherical. Another case is that of a line source, which radiates what are commonly termed cylindrical waves.

Thus the total power in the wave will remain constant if no attenuation is assumed, but the intensity (i.e. power per area) decreases as the wave spreads out from the source. Whether the spreading will be spherical, cylindrical, or some combination of both depends on the type of source and the geometry of the medium in which the wave is propagated. Intensity of a spherically spreading wave is inversely proportional to the square of the distance from the source, and pressure is inversely proportional to the distance from the source, or (16),

$$I \text{ (spherical)} \sim \frac{1}{r^2} \tag{10a}$$

and

$$p \text{ (spherical)} \sim \frac{1}{r} \ . \tag{10b}$$

For cylindrical spreading, the following relations hold (17):

$$I \text{ (cylindrical)} \sim \frac{1}{r} \tag{10c}$$

$$p \text{ (cylindrical)} \sim \frac{1}{\sqrt{r}} \ . \tag{10d}$$

The transmission of signals between the Bear Cut instrument tower and the pier provides the students with the opportunity to study the effects of spreading over a distance of approximately 600 feet. Since there is less receiving than transmitting equipment to be transported, the tower is a more likely place for receiving than for transmitting signals. Also the channel is divergent (i.e. it gets deeper) when

transmitting in this direction, so published information on propagation in a divergent channel (18) may be of some use in interpreting results. The sound pressure levels measured at the one meter separation or the data calculated from equivalent circuit parameters serve as approximate references for comparison of the sound pressure levels measured at a separation of about 180 meters. The propagation loss, the reduction in intensity between the reference point and the receiver, can be calculated in terms of sound pressure levels and expressed in decibels (19)

$$N_W = 20 \log \frac{p}{p_0} . \tag{10e}$$

This propagation loss will be almost entirely due to spreading, since the attenuation of sound due to the medium will be negligible at the distance and operating frequencies (20 KHz maximum) involved.*

An instructive experiment which may be included in the laboratory program at any convenient point demonstrates the techniques involved in the reciprocity calibration of transducers. The reciprocity theorem, laid down by Lord Rayleigh in The Theory of Sound, states that in any system composed of bilateral impedances, if an output in branch B caused by an input in branch A is measured and compared with a measured output in branch A caused by an input in branch B, then the ratios of the outputs to the corresponding inputs will be equal (20). The efficiency in transmission of most piezoelectric transducers is related to their sensitivity in reception, and piezoelectric transducers generally satisfy the conditions of the reciprocity theorem (21).

The receiving sensitivity of a transducer used as a hydrophone and the transmitting sensitivity of the same transducer used as a

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*See Figure 1.1, Tolstoy and Clay, page 5.

projector are related by the reciprocity theorem as shown in the following relations (22):

$$S_R = \frac{V_R}{p_R} \tag{11a}$$

$$S_T = \frac{p_P}{I_P} \tag{11b}$$

$$\frac{p_P}{I_P} = \frac{V_R}{Q} \tag{11c}$$

where the symbols are defined as RMS or average values of the following:

$V_R$ - - voltage out of the hydrophone,

Q - - strength of a sound source at the hydrophone produced by pressure out of the projector,

$p_R$ - - pressure into the hydrophone due to Q,

$p_P$ - - pressure out of the projector as measured at the hydrophone,

$I_P$ - - input current to the projector.

Since the hydrophone will be located at a distance r from the projector, the pressure transmitted by the projector will be reduced as it is propagated through the medium. The transmitted and received pressure, and hence the transmitting and receiving sensitivities, can be related through the reciprocity parameter, J, however (23). Now,

$$S_R = JS_T, \tag{11d}$$

where

$$J = \frac{2x10^{-7}\lambda r}{\rho c} \quad \frac{cm^4 \, sec}{gm} . \tag{11e}$$

$\lambda$, r, $\rho$, and c are all known from the parameters of the experiment, so J can be calculated.

The experiment demonstrating the absolute calibration of transducers using the reciprocity theorem calls for the use of three transducers. The transducers and the parameters that will be measured are shown schematically in Figure 7. Transducer A is the transducer to be calibrated. It will be used both as a projector and as a hydrophone and must satisfy the conditions of the reciprocity theorem. Transducer B is used only as a projector, so its receiving characteristics are of no concern. Transducer C is used only as a hydrophone, so its transmitting characteristics are of no concern. As indicated in Figure 7, three sets of measurements are made. Using B as a projector and C as a hydrophone, the input current of B, $I_1$, and the output voltage of C, $V_1$, are measured. Using A as a projector and C as a hydrophone, the input current of A, $I_2$, and the output voltage of C, $V_2$, are measured. Using B as a projector and A as a hydrophone, the input current of B, $I_3$, and the output voltage of A, $V_3$, are measured. Applying the reciprocity relation to transducer A, the transmitting and receiving sensitivities can be computed from the following equations:

$$S_{TA} = \sqrt{\frac{(I_1)(V_2)(V_3)}{(V_1)(I_2)(I_3)(J)}} \tag{11f}$$

$$S_{RA} = \sqrt{\frac{(I_1)(V_2)(V_3)(J)}{(V_1)(I_2)(I_3)}} \tag{11g}$$

The transmitting sensitivity of transducer B and the receiving sensitivity of transducer C may also be calculated,

$$S_{TB} = \sqrt{\frac{(V_1)(I_2)(V_3)}{(I_1)(V_2)(I_3)(J)}} \tag{11h}$$

and

$$S_{RC} = \sqrt{\frac{(V_1)(V_2)(I_3)(J)}{(I_1)(I_2)(V_3)}} \quad (24). \tag{11i}$$

Inaccuracies in the experiment are primarily due to reflections from structures in the water, from the water surface, and from the bottom in the area in which the experiment is conducted. If the transducers being calibrated are positioned in depth midway between the surface and the bottom, minimum pressure from surface-or-bottom-reflected signals will be encountered. If it is required that the signals reflected from the surface and the bottom are to be 20 db below the direct-path signal, then the relation between water depth, h, and the horizontal separation, r, must be (25)

$$h \geq 10r. \tag{12}$$

Horizontal separation can be no less than about 40 cm at an operating frequency of 20 KHz due to far field considerations. The depth of water in Bear Cut at the pier is about 340 cm at mid-tide and 370 cm at high tide, so that the minimum depth criterion cannot be met if the calibration is conducted at the pier. Also the transducer hanger in use (see Appendix B) does not position the transducers at a lateral distance great enough to prevent significant reflections from the pier structures. Sites other than the pier may be more suitable for the conduct of this experiment, but at present they are inconvenient due to transportation of equipment, and lack of electrical power outlets and facilities for monitoring the transducers. Although data obtained in this experiment cannot be used for absolute calibration standards, the techniques for a reciprocity calibration are graphically demonstrated to the students.

One of the techniques used in practical applications of underwater acoustics is signal processing to improve the ability to detect weak signals. Detection of a signal in background noise can be viewed as a function of the signal-to-noise ratio at the receiving system (26). To demonstrate this principle to the students, an experiment has been devised to compare various types of filters and filter combinations.

The experiment calls for the detection of a signal transmitted between the pier and the instrument tower, using the standard equipment. The transmitted signal is reduced to the level of minimum detectability at the hydrophone. Various combinations of high-pass, low-pass, and band-pass filters are inserted in the receiving system, and the minimum detectable signal is measured for each filter or filter combination. Background noise is also measured in each instance. The minimum detectable signals for the various filtering conditions are then compared to determine the optimum condition. A further demonstration of the effect of filtering is achieved through the use of a band-pass filter. The students detect and record the minimum detectable signal level with the filter set for a relatively wide bandwidth. Without changing the signal level, the bandwidth of the filter is significantly reduced. The resulting increased signal to noise condition is compared to the previous case.

When dealing with propagation ranges of greater than the 600 feet from the pier to the tower, a variety of propagation anomalies may be encountered, depending on the water temperature distribution as a function of depth and on the boundary conditions at the interfaces of the channel. In particular, there may exist acoustic ray focusing effects. Focusing occurs when a number of sound rays converge at the

same point. This may be caused by reflections from the boundaries of the channel (which will not always conform to the perfectly smooth mathematical model employed in much basic propagation theory), and in some cases focusing may be due to refraction of sound rays caused by varying propagation velocities in the medium. The temperature differences in the medium will have the most pronounced effect on sound propagation velocities in Bear Cut. Because the channel is shallow, however, it is unlikely that temperature gradients significant enough to produce detectable propagation anomalies will be present except in rare instances. During propagation experiments, it is nevertheless suggested that a thermistor string or some other temperature-sensing device be employed to check the variation of water temperature with depth. In addition to providing a record to aid in the interpretation of experimental data, such measurements would serve a useful academic purpose in demonstrating to graduate student ocean engineers some of the techniques and equipment employed in ocean measurements. Because the bottom contour of the channel is not known in detail and extensive analysis is required to correlate surface wave action with acoustic propagation, it will be difficult to predict mathematically the location of focusing zones. At various distances from the sound source and at various depths in the channel, these focusing zones will be detectable with hydrophones due to the increased sound pressure levels there as compared to the sound pressure levels in the adjacent areas.

With transmitting equipment at the tower, students man a small boat and use portable, battery powered, receiving equipment to investigate longer range propagation. Sound pressure levels are measured at various distances and depths. Simultaneously, azimuths to prominent landmarks

are measured with a standard marine sextant. The azimuths are later plotted with the pressure levels so that acoustic pressure as a function of distance is presented on a chart.* Depths of maxima and minima pressure can be located while taking measurements by lowering and raising the hydrophone. Propagation characteristics between points of measurement can be extrapolated to provide a broad picture of the propagation conditions in Bear Cut on a given day. Propagation will vary with environmental conditions, suggesting that not only water temperature, but as many environmental parameters as feasible should be measured so that future comparisons can be made.

When an acoustic signal is propagated in a medium bounded by surfaces from which the signal will be reflected, a propagation phenomenon occurs which is termed the "waveguide effect." A prototype for the medium leading to this type of propagation is a homogeneous body of water of constant depth bounded by a perfectly smooth bottom and surface. As acoustic rays are repeatedly reflected from the surface and from the bottom, the various rays which make up a signal will interact with one another. The interaction may take the form of constructive or destructive interference. For constructive interference, the reinforcing signals must be in phase when they converge at the same point, and they tend to cancel. This leads to the equation of normal mode propagation:

$$f_n = \frac{c}{4h \sin \theta} \left(2n - 1 + \frac{\varepsilon}{\pi}\right), \tag{13a}$$

where n = 1, 2, 3, .........

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*The Key Biscayne Quadrangle Sheet, scale 1:24,000, is recommended for this purpose. Marine charts are too small in scale.

This equation indicates that for each frequency, $f_n$, at which an acoustic signal is generated, only those acoustic rays which leave the source at angle $\theta$ will be propagated in a waveguide. Another way of interpreting this equation is to assume that a source, operating at a given frequency, will propagate at an angle $\theta$ dependent on the mode, n. The depth of the water is h, and $\varepsilon$ represents the phase shift caused by the signal being reflected from the bottom. The limiting case of (13a) occurs when n = 1 and $\theta = 90°$. In this case the phase shift $\varepsilon$ is zero. The resulting equation defines the minimum frequency of waveguide propagation, or the "waveguide cutoff frequency":

$$f_{min} = \frac{c}{4h} . \tag{13b}$$

This is the lowest frequency at which propagation in a waveguide can occur (27).

The laboratory medium, Bear Cut, approximates the prototype medium in that it has an almost constant depth between the pier and the instrument tower and is bounded by relatively smooth surfaces. The waveguide effect can therefore be demonstrated by lowering the operating frequency of a projector to the point where cutoff occurs. The cutoff frequency for Bear Cut, assuming propagation velocity, c, to be 1500 meters/second and the average depth of the waveguide to be about 4 meters (13 feet), will be approximately 94 Hz. This frequency is too low for the efficient transmission of signals using the laboratory's sound projectors (Edo models 244C and 284). The model J9 electrodynamic transducer, manufactured by the Chesapeake Instrument Corporation and Dyna-Empire, Incorporated, can be effectively operated at frequencies as low as 40 Hz.

The experiment demonstrating the cutoff frequency of a waveguide uses a J9 projector to generate an acoustic signal. Two Clevite CH-17

hydrophones are employed, one in close proximity to the projector at the pier, another at the instrument tower. The first hydrophone is used to monitor the output pressure of the projector, thereby insuring that a constant acoustic output is maintained as the operating frequency is lowered. As the frequency is lowered while constant acoustic intensity is maintained at the projector, the standard receiving equipment at the tower is used to indicate the frequency at which no acoustic signal or a greatly reduced signal is received.

The use of more than one transducer for sound generation or receiving gives rise to the concept of transducer arrays. One way to provide an acoustic beam rather than an omnidirectional pattern, is to employ an array of several transducers. One typical array which can be constructed with the laboratory facilities available is a multi-spot array which consists of several transducers in a line, as illustrated in Figure 8. In this diagram, the transducers are separated by "a" units, and the observer point is indicated by P. For an n element array of this type,

$$\frac{p(\theta)}{p_0} = \frac{\sin n \psi}{n \sin \psi}, \tag{14a}$$

where $p(\theta)$ is the pressure at angle $\theta$, $p_0$ is the pressure at $\theta = 0$, and

$$\psi = \frac{ka}{2} \sin \theta = \frac{\pi a}{\lambda} \sin \theta. \tag{14b}$$

As seen by this equation, the pattern depends on the element spacing a. Usually, the maximum distance is $a = \frac{\lambda}{2}$. Larger separations will yield a different type of pattern than the one usually desired.

The expressions above were derived for a projector array on the basis of adding the pressures in the medium from each source. The

resulting pattern develops from the phase differences due to the different path lengths between each source and P.

In the case of hydrophones, similar considerations apply to receiving directivity patterns achieved through the use of arrays. A single sound projector is used, but an array of hydrophones is employed as the receiving system. The pressures have a differing phase at each hydrophone, and summing the signals from individual hydrophones yields the desired pattern (28). Each hydrophone requires an isolating amplifier to prevent interactions.

To demonstrate the directivity pattern of a transducer array, an experiment has been devised in which four hydrophones are mounted at the end of one of the transducer hangers as shown in Figure 9. The separations between the hydrophones are each one-half wavelength ($\frac{\lambda}{2}$) apart in order to obtain the desired directivity pattern. With the sound projector and standard transmitting equipment on the pier, an acoustic signal is transmitted to the instrument tower, where the hydrophone array receives the signal. Each of the four hydrophone signal lines are isolated and summed, yielding a resultant signal as the detected output. The hydrophone array axis is oriented at various angles in order to measure the directivity pattern.

## III. CONCLUSIONS AND RECOMMENDATIONS

The experience gained in the preparation of this thesis has demonstrated that an open water, underwater acoustics laboratory for graduate level students can be effectively organized and instituted. The practical experience of such a laboratory is a valuable and almost necessary supplement to lectures on theory.

After the initial basic experiments, it is desirable that additional facilities be incorporated into the laboratory in order that more advanced experiments can be conducted both in the laboratory course and as part of the graduate student research program. The following paragraphs suggest experiments that could be conducted with expanded laboratory facilities.

Probably the single most significant facility that could be added to the laboratory would be pulse-generating equipment. Some of the experiments accomplished with continuous wave operation could be made more accurate through the use of pulsed operation. For instance, the reciprocity calibration of transducers can be modified favorably if pulsed operation is employed, since reflections would be greatly reduced (29). New experimental possibilities also become feasible. Demonstrations of the effects of a dispersive medium (30) could possibly be accomplished by generating a shaped pulse (e.g. a rectangular wave) at the pier and investigating the shape of the wave after transmission with a hydrophone/oscilloscope combination at the instrument tower.

With a high frequency carrier and pulsed modulation, reflections

off the bottom of the channel could be detected. By measuring the pressure amplitudes of pulses with different arrival times, comparisons could be made between direct-path pulses and bottom-reflected pulses. Data could be analyzed to compute the bottom reflection coefficient (31). It is probable that such reflection experiments would have to be conducted at frequencies higher than those possible with the presently available equipment.

Pulsed operation would also make possible echo-ranging experiments. An acoustic reflector in Bear Cut could be employed to demonstrate most aspects of the sonar equations (32). An advanced project might involve the design of a transponder to amplify echoes at the operating frequencies of the equipment in use.

A variety of experiments are feasible with transducer arrays. Varying the phase of the elements of a projector array could produce electrically steered acoustic beams, while a variation in the power transmitted by various elements could produce shaded arrays (33).

Other possibilities for research include the investigation of doppler shifts and the effects of time-varying phenomena on propagation. There will undoubtedly be many more applications for the laboratory facilities for both students and faculty.

Underwater acoustics programs at educational institutions have gained in stature as a result of government interest in applications of underwater acoustics for national defense. Also, a new generation of acoustic devices for ocean research and development is presently spawning. Included in this area are navigation and positioning systems, telemetering devices, and submerged instruments activated by acoustic signals. An effective instructional program in underwater acoustics

requires a laboratory course. Consequently, the facilities and the course described in this thesis will be significant factors in the continued expansion of the Ocean Engineering Department of the University of Miami.

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(6) *Ibid*., Eq. (677) and Eq. (678).

(7) *Ibid*., pp. 223-26.

(8) *Ibid*., Eq. (145).

(9) *Ibid*., Eq. (147).

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(14) Bartberger, *op. cit*., pp. 36-41.

(15) Bartberger, *op. cit*., Eq. (822).

(16) Bartberger, *op. cit*., pp. 36-38.

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(22) Bartberger, <u>op. cit</u>., Eqs. (834), (835), and (836).

(23) Bartberger, <u>op. cit</u>., pp. 301-302.

(24) Bartberger, <u>op. cit</u>., pp. 306-307.

(25) Bartberger, <u>op. cit</u>., Eq. (858).

(26) Urick, <u>op. cit</u>., pp. 304-305.

(27) Bartberger, <u>op. cit</u>., pp. 168-73.

(28) Bartberger, <u>op. cit</u>., pp. 238-53.

(29) Bartberger, <u>op. cit</u>., pp. 310-12.

(30) Tolstoy and Clay, <u>op. cit</u>., pp. 40-48.

(31) Tolstoy and Clay, <u>op. cit</u>., pp. 23-28.

(32) Urick, <u>op. cit</u>., pp. 16-27.

(33) Bartberger, <u>op. cit</u>., pp. 263-67.

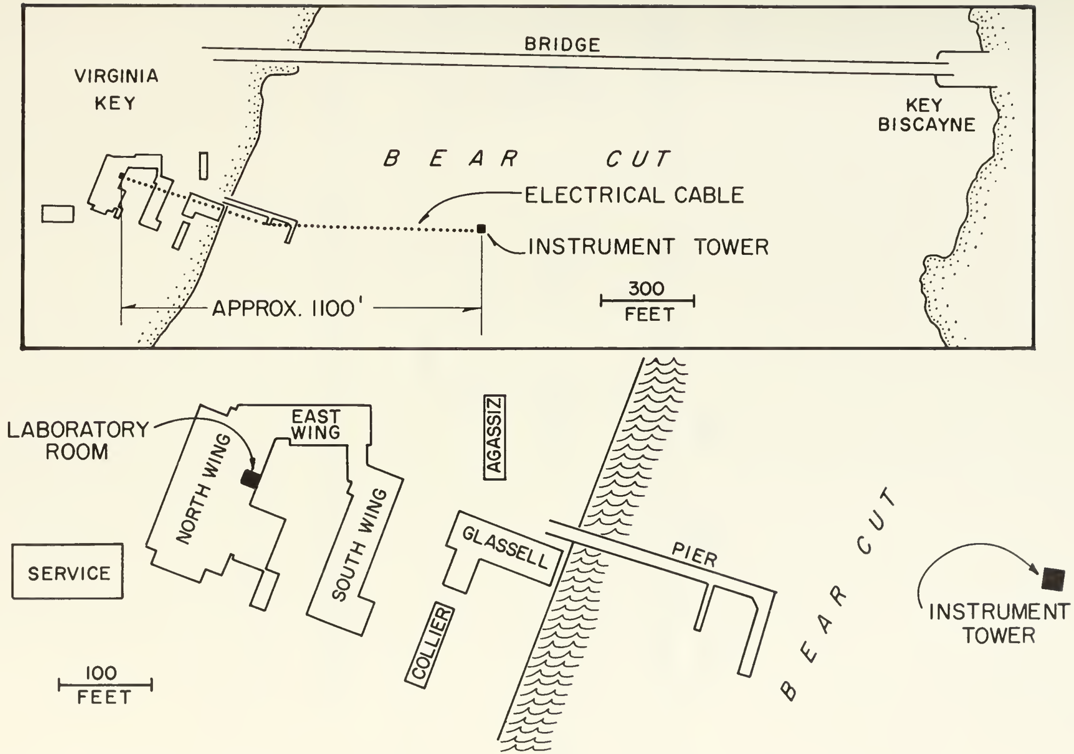



Fig. 1. Diagram of the Institute of Marine and Atmospheric Sciences Complex.

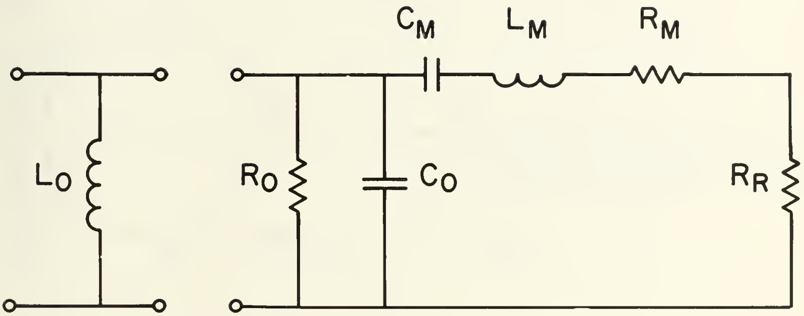



Fig. 2. Equivalent Circuit of a Piezoelectric Transducer.

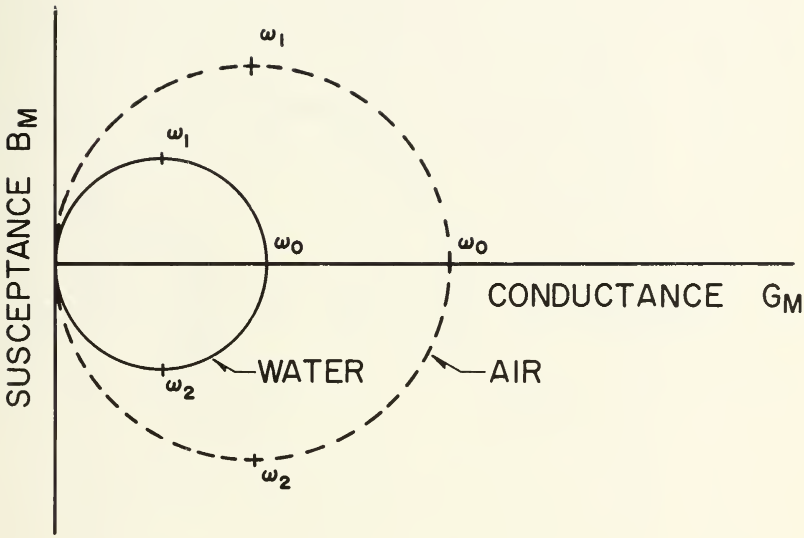



Fig. 3. Admittance Circles of a Piezoelectric Transducer.

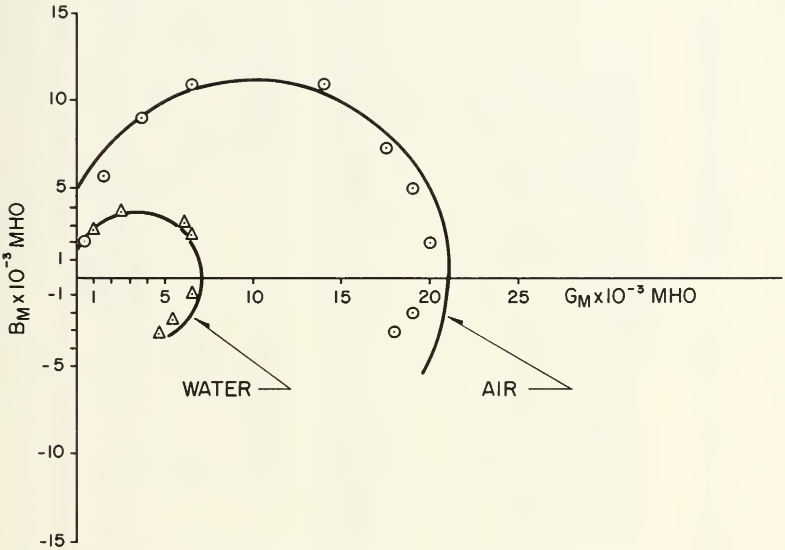



Fig. 4. Measured Admittance Circles of a Piezoelectric Transducer.

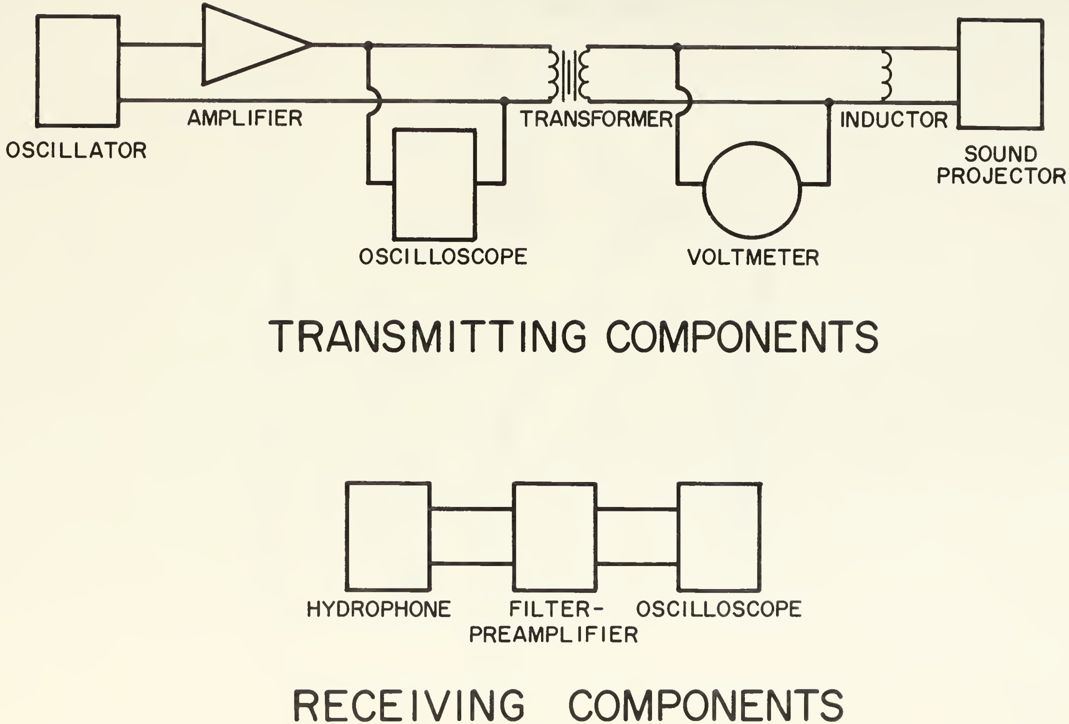



Fig. 5. Transmitting and Receiving Components Used in Various Experiments.

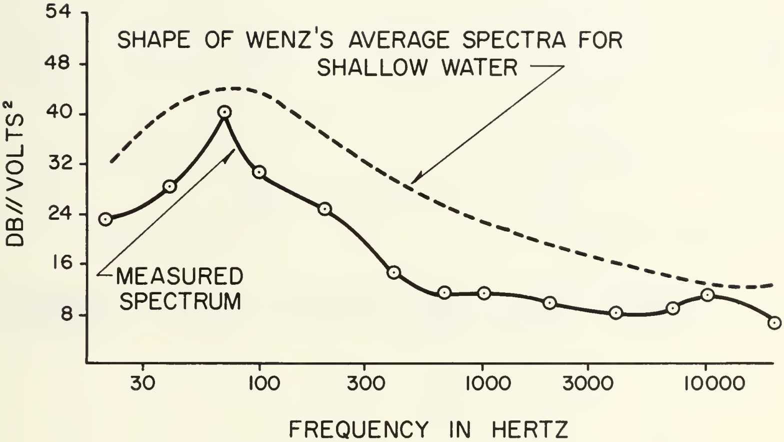
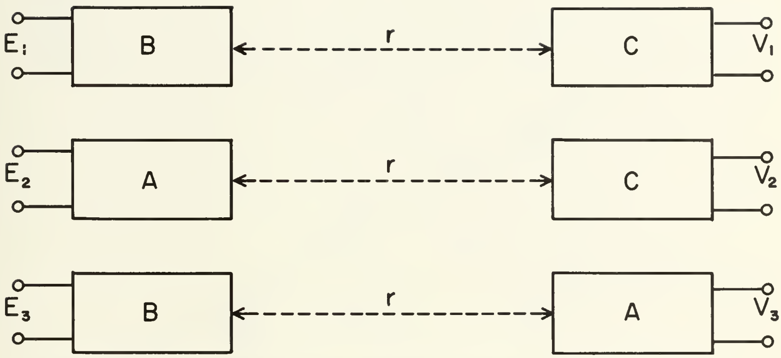



Fig. 6. Measured Acoustic Noise Spectrum and Published Spectrum.




| MEASUREMENT NUMBER | PROJECTOR | HYDROPHONE | INPUT VOLTAGE | INPUT* CURRENT | OUTPUT VOLTAGE |
|---|---|---|---|---|---|
| 1 | B | C | $E_1$ | $I_1$ | $V_1$ |
| 2 | A | C | $E_2$ | $I_2$ | $V_2$ |
| 3 | B | A | $E_3$ | $I_3$ | $V_3$ |

* INPUT CURRENT IS CALCULATED FROM THE VOLTAGE ACROSS A STANDARD RESISTOR INSERTED IN THE INPUT CIRCUIT.

Fig. 7. Diagram and Table for Reciprocity Calibration Experiment.

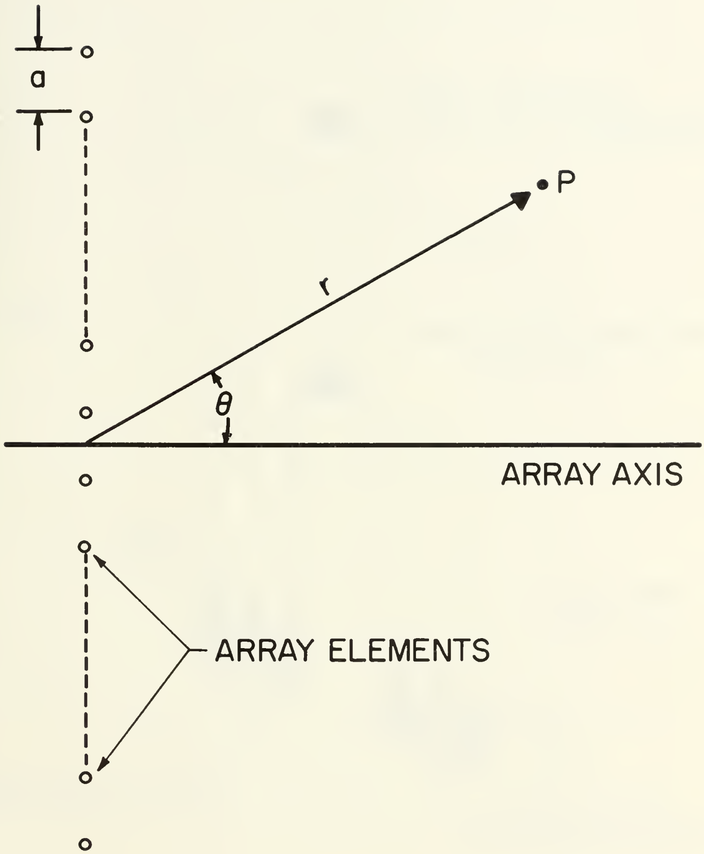



Fig. 8. Multi-Spot Array Diagram.

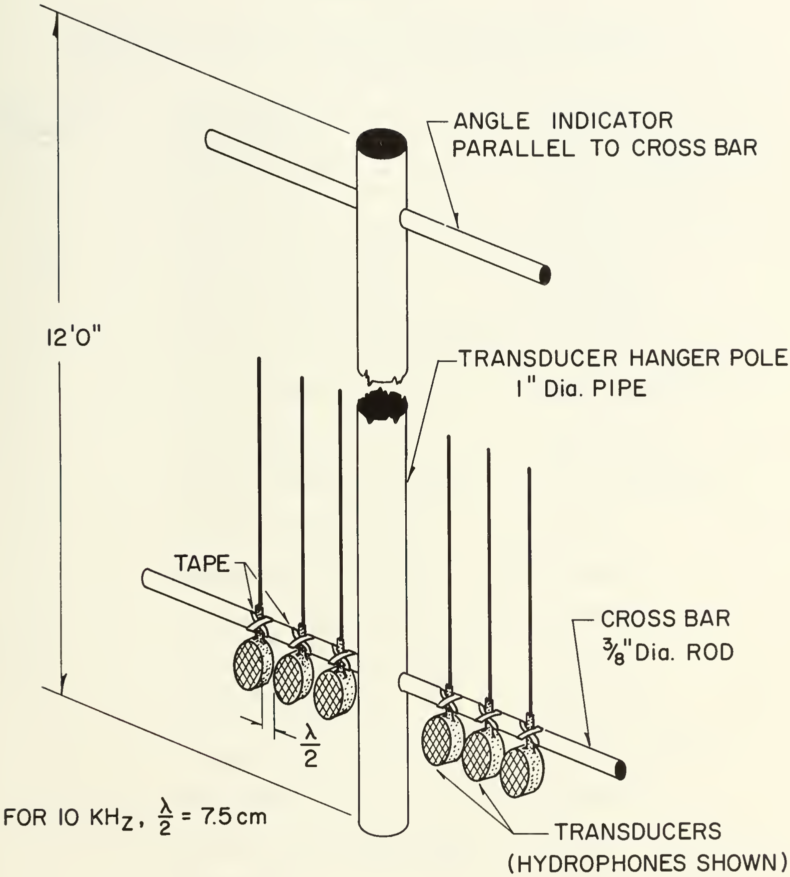



Fig. 9. Method of Mounting Transducer Array.

APPENDIX A

Underwater Acoustics Laboratory Equipment Inventory

| Quantity | Description | Equipment |
| --- | --- | --- |
| 10 | Edo Model 244C | Sound Projector |
| 2 | Edo Model 284 | Sound Projector |
| 10 | Clevite Model CH-17 | Hydrophone |
| 2 | Clevite Model CH-24 | Hydrophone |
| 2 | Hewlett-Packard Model 200 CD | Oscillator |
| 2 | Allied Model 935 | Power Amplifier |
| 2 | Tektronix Type 504 | Oscilloscope |
| 2 | General Radio Type 1232-A | Filter/Amplifier |
| 1 | Krohn-Hite Model 3500 | Filter |
| 1 | Ballantine Model 300H | Voltmeter |
| 1 | Ballantine Model 302C | Voltmeter |
| 1 | RCA Voltohmyst Type WV-98C | Voltmeter |
| 1 | Dranetz Model 301A | Phase Meter |
| 1 | Dranetz Model 320A | Impedance Meter |
| 2 | Fanon Model IC-10 | Transceiver |
| 1 | Hewlett-Packard Model 524D | Frequency Counter |
| 1 | Aluminum | Transducer Hanger |

Various electrical components and laboratory tools.

# APPENDIX B

To facilitate the handling of transducers the author has designed the mechanical transducer hanger shown in photographs on the following pages. The hanger was constructed of aluminum by the IMAS Metal Shop. It has proven satisfactory for laboratory use, and similar designs are recommended for other hangers which may be required by the laboratory. A cross-bar device such as shown in Figure 9 is easily adapted for positioning transducer arrays. A mechanical angle-indicator can be positioned at the top of the array pole so that angles of the array axis can be read.

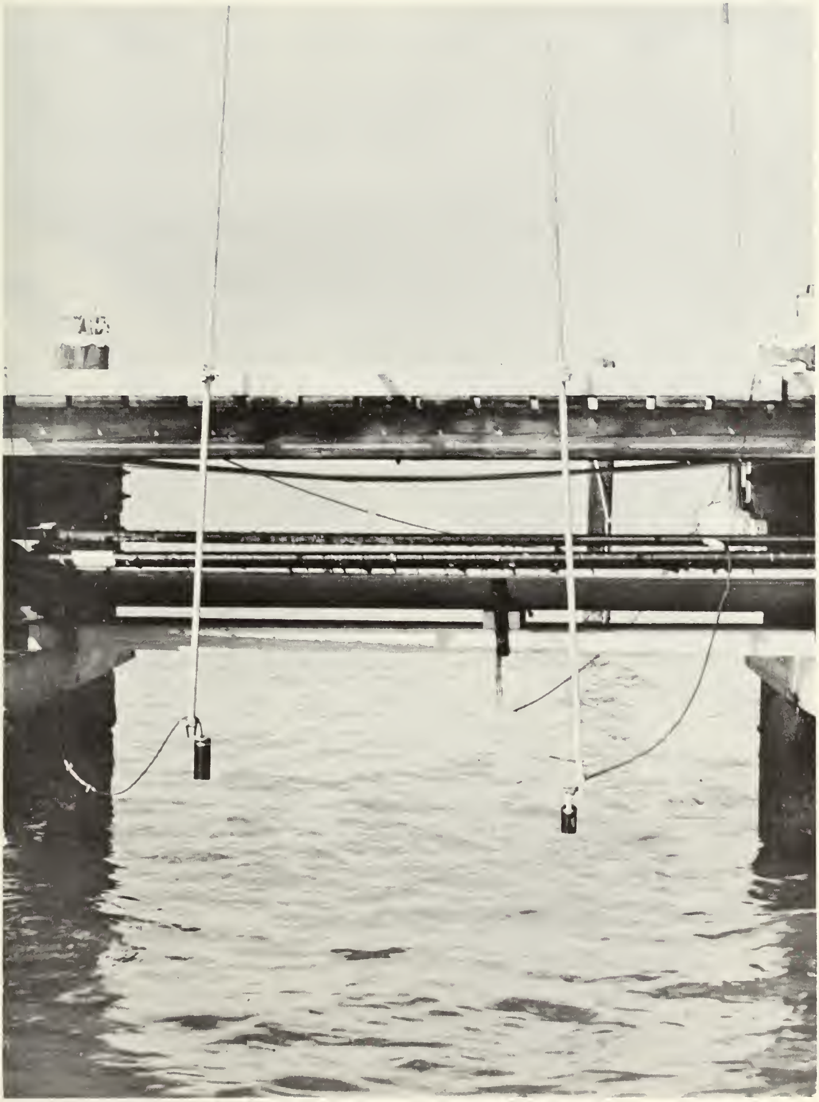


Fig. B-1. Laboratory Transducer Hanger in Place on IMAS Pier.

Fig. B-2. Close-up of Transducer Hanger Clamping Devices.

# VITA

Wiley George Grantham was born in San Pedro, California, on July 6, 1941. His parents were Herbert George Grantham and Marie Knauff Grantham. He received his elementary education in various public schools in California, Ohio, North Carolina, and Virginia. His secondary education was received in North Charleston High School, North Charleston, South Carolina. In July 1959 he entered the United States Naval Academy, Annapolis, Maryland, from which he graduated with the B.S. degree in June 1963. Upon graduation he received a commission as an officer of the United States Navy. In June 1970 he held the rank of Lieutenant. From 1963 to 1968, he served on three destroyers of the Atlantic Fleet.

In September 1968 he was admitted to the Graduate School of the University of Miami, having been a selectee in the Navy Postgraduate Program. He completed the requirements for the degree of Master of Science in June 1970.

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